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AFAPL-TR-76-12

ADB010387

LASER IGNITION OF TITANIUM

Components Branch
Turbine Engine Division

March 1976

TECHNICAL REPORT AFAPL-TR-76-12

FINAL REPORT FOR PERIOD 1 JUNE 1974 - 1 AUGUST 1975

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This technical report has been reviewed and is approved for publication.

CHARLES W. ELROD, JR., GS-13
Project Engineer

FOR THE COMMANDER

JAMES L. RADLOFF, Major, USAF
Chief, Components Branch
Turbine Engine Division

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: (14) AFAPL-TR-76-12	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): (6) Laser Ignition of Titanium.		5. TYPE OF REPORT & PERIOD COVERED: Jun[redacted]1974 - Aug[redacted]1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): (10) Charles Elrod, Richard Rivir, Douglas Rabe		8. CONTRACT OR GRANT NUMBER(s): (16) F-3066
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Air Force Aero-Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, OH 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (17) 30661[redacted]
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Aero-Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, OH 45433		12. REPORT DATE: (11) March 1976
		13. NUMBER OF PAGES: 30
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 31 p.		15. SECURITY CLASS. (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Titanium Combustion
Laser Test
Metal Fires

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program was directed towards the determination of using a laser as an ignition source for titanium combustion studies. A sample of titanium was located downstream from a subsonic nozzle with the edge facing the flow. The front, upper tip of the sample was ignited and allowed to burn freely aided only by the transport of oxygen by the wind tunnel. Although the pressure was ambient the air was delivered at 90° - 500°F and flow rates from Mach number .2 to Mach number .7. Sustained combustion was obtained at low Mach numbers and high temperature but not at low Mach numbers and low temperatures.

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20. Abstract (Cont'd)

The low Mach number burns were more severe than the high Mach number burns, i.e., more metal consumed before flowout. In all cases the fire progressed laterally but not significantly in the vertical direction.

FOREWORD

This report contains the results of research on laser ignition of titanium at ambient pressure and elevated temperatures in a flowing air stream performed in the Turbine Engine Division. The study was conducted by Charles Elrod, Richard Rivir of the Components Branch of the Turbine Engine Division and Douglas Rabe of the Power Distribution Branch of the Secondary Power Division. The work was performed under Project 3066, Task 306610, "Mechanical Systems Technology," and Work Unit 30661005, "Compressor Rub Test Facility," during the period June 1974 to August 1975. The authors appreciate the support of Walter Steuble, Paul Vore, and Eugene Francescone during the execution of the test program.

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INTRODUCTION

With the increasing use of titanium in the aerospace industry, the question of safety and, in particular, metal combustion has been raised. Past experience in space related programs has shown titanium to be vulnerable to ignition and sustained combustion under certain environmental conditions.

Although ignition can be attained by increasing the metal temperature to 2900°F, sustained combustion requires a replenishing supply of oxygen. The aircraft and engine environment is conducive to the initiation of titanium combustion, but the exact nature of the problem and the degree of hazard proposed with the use of titanium has not been established.

Some work was also conducted in conjunction with reactor failures at Oak Ridge, Tennessee, resulting in metal combustion. Stanford Research Institute investigated the problem at some depth [Ref. 1]. An experiment was conducted using titanium rods which were fractured in tension, thus exposing fresh metal to an oxygen environment. The effect of temperature and pressure on the ignition characteristics of titanium exposed in this manner are shown in Figure 1. This curve has been used as a reference guide for the application of titanium in the aircraft industry.

Recently, the general acceptability of this data has been questioned [Refs. 2 and 3]. Ignition and propagation have occurred outside the limits shown in Figure 1. As a result,

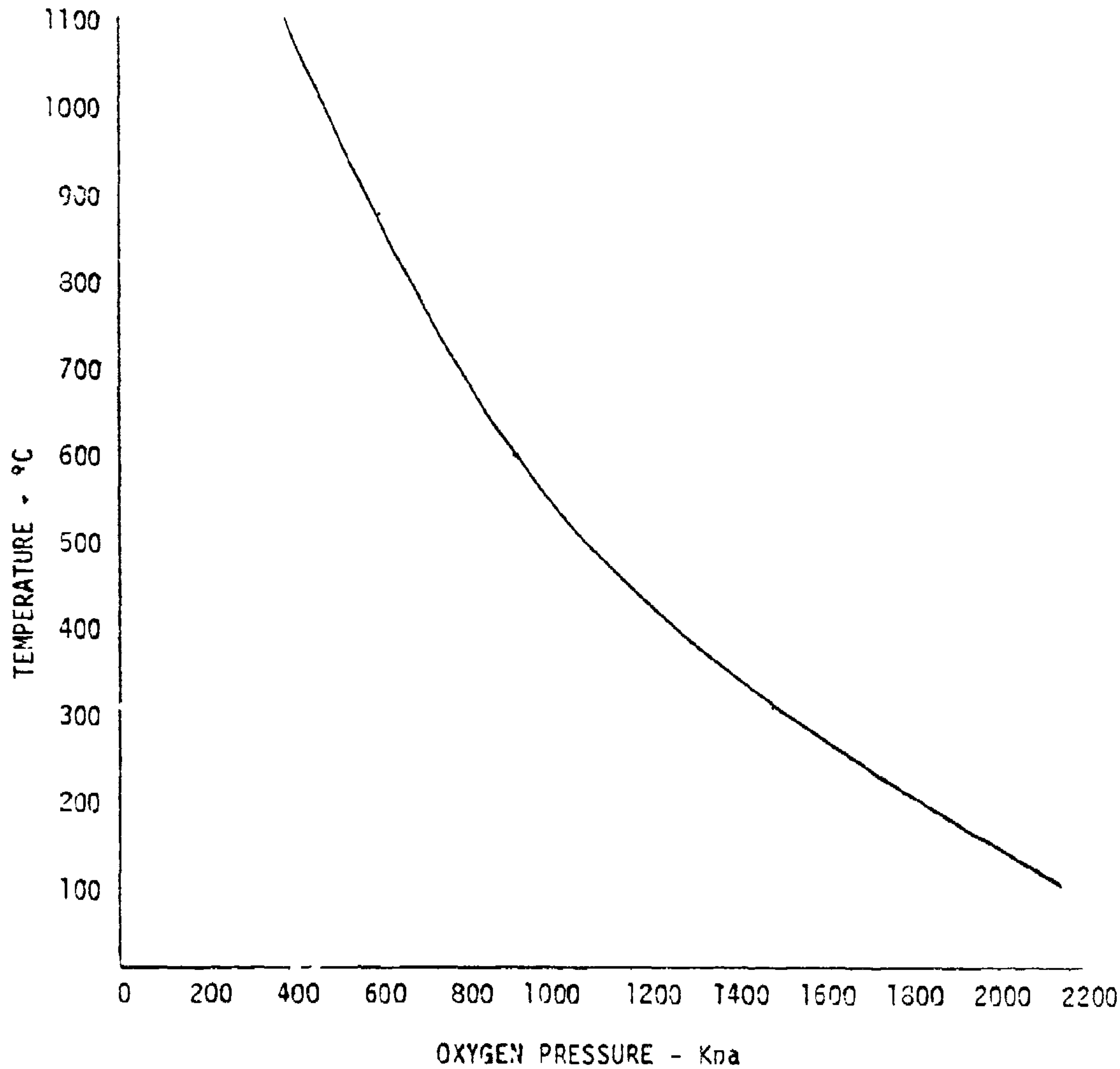


Figure 1. Ti Ignition in Oxygen

some additional testing is in progress at the Air Force Aero-Propulsion Laboratory to further define the characteristics of titanium ignition and its self-sustained combustion.

A study was conducted [Ref. 4] which used a melting wire as the ignition source. The sample was exposed to varying temperature, pressure, and flow rate. A wire placed in close proximity to the sample was melted by a large flow of current. The melt impinged on the sample and ignition occurred. This test program did suggest a trend for titanium ignition and propagation, but was limited in the low flow range. The use of a melting wire produced another problem. The ignition site could not be pre-determined and in some preliminary tests the sample was missed altogether. This uncontrollable ignition source was determined to be an undesirable limitation and a new ignition source was required.

A laser was selected and a series of preliminary tests run to determine its feasibility as a controlled energy source. This report is a summary of those initial tests.

DESCRIPTION OF THE ELECTRO-AERODYNAMIC LASER:

The electro-aerodynamic laser is a fast flow, electrically excited CO_2 laser; the cavity of 5.24 cm x 76.2 cm x 91.4 cm. The cavity is excited by a flow discharge between multiple electrodes located at the entrance and exit of the flow channel. Stimulated emission of the cavity flow was obtained in this series of tests by an external master oscillator. The master oscillator beam is single mode and passes through an aperature

prior to entry into the laser cavity. The MO beam enters the cavity approximately normal to the flow direction and then makes 17 Z paths across the cavity. The observed beam quality is estimated from plexiglass burns to be better than two due to small values of $\frac{\Delta\rho}{\rho}$ which result from the low cavity pressure and subsonic channel flow.

The master oscillator is blocked by shutters on the first pass through the cavity. The cavity and power supplies for excitation of the flow discharge are continuous. The mirrors which provide the 17 Z paths are heat sinks limiting the laser lasing time to 2.0 seconds maximum or nominally 1.0 second without beam distortion. The master oscillator shutters are operated by electric solenoids. The on-off time of the laser beam can be controlled reproducibly to the nearest tenth of a second. The on time is read to the nearest hundredth of a second. The nominal beam power is approximately 10 KW. Beam power is measured with a re-entrant calorimeter designed by the National Bureau of Standards and by a Coherent Radiation, CO_2 detector which measures the power back-scattered from the surface of a salt flat which is in the output beam inclined at a small angle to the direction of the beam propagation. The salt flat is usually calibrated against the re-entrant calorimeter and used as an indicator of the power level during a test, in which a portion of the power in the beam is absorbed.

AIR SUPPLY FOR LASER TI COMBUSTION:

The blowdown wind tunnel used for investigating aerodynamic effects in conjunction with the Electro-Aerodynamic Laser (EAL)

was used as the controlled air flow over the Ti sample. The blowdown tunnel employs a subsonic nozzle with an exit diameter of four inches. Free jet Mach numbers up to .8 were run during this investigation. A pebble bed heater is in series with the blowdown tunnel line between the high pressure reservoir and the nozzle plenum. The pebble bed is composed of (steel) pebbles to minimize sand blast effects which are encountered with high temperature $Zr\ O_2$ or $Al\ O_2$ pebbles. The maximum temperature of the electrically heated bed is 650°.

The length of the air pulse is nominally 10 seconds for subsonic flow. A typical subsonic run showing plenum pressure and temperature is shown in Figure 2.

TI COMBUSTION RUN SEQUENCE:

A typical run sequence would be to initiate the glow discharge in the main lasing cavity where the lasing medium is continuously circulating, the external master oscillator is on continuously. After adjusting the cavity current to the desired value (proportional to the desired power output level of the laser), the wind tunnel flow is started. The tunnel reaches equilibrium in approximately two seconds. When tunnel equilibrium is reached, the shutters on the master oscillator are opened for a predetermined length of time; for example: .48 second, and then closed. The high speed camera would normally be started at the time the tunnel is turned on.

The laser beam was brought down parallel to the tunnel axis and then turned normal to the path of the free jet and onto

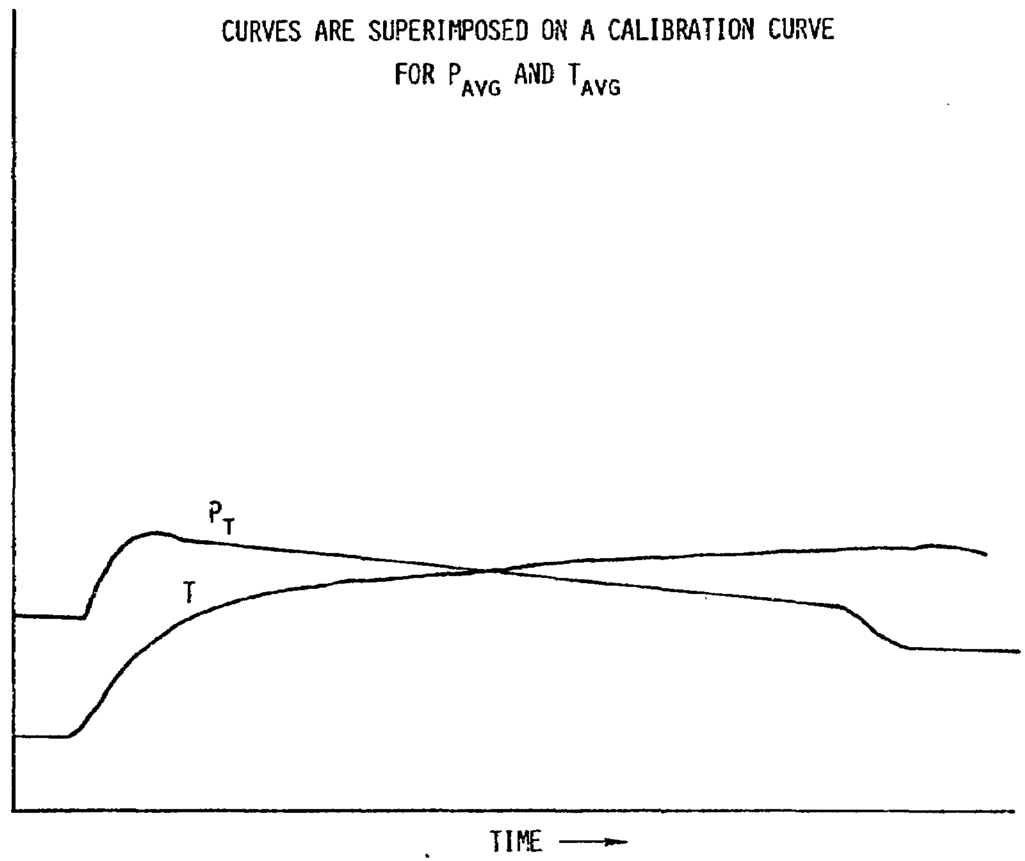
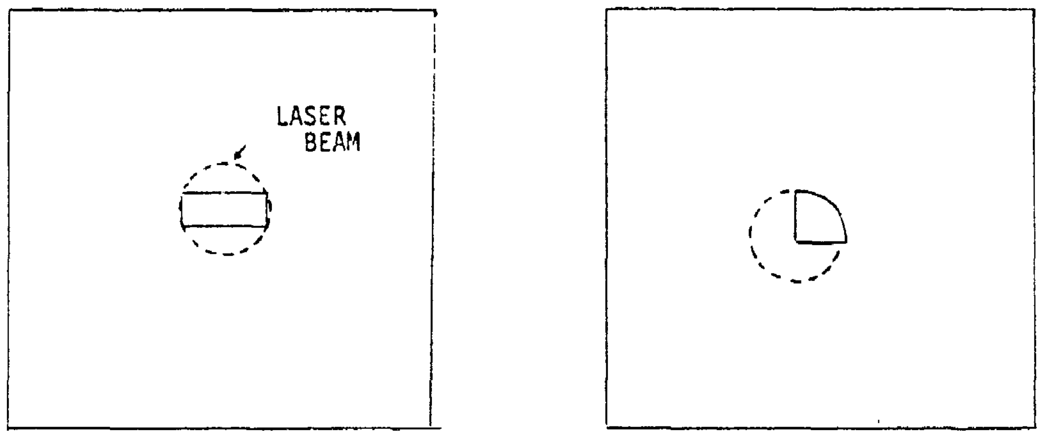


Figure 2. Pressure/Temperature Traces

the sample. Samples are normally inclined at small angles to the incident laser beam to prevent reflection and self-excitation of the lasing cavity. The output laser beam was aperatured with both a corner and a slot to control the point of combustion initiation on the Ti sample. The aperatures are shown in Figure 3. The aperatures are copper plates which were placed in the expanding laser beam. The re-entrant calorimeter was placed behind the sample outside the free jet. Both the re-entrant calorimeter and the salt flat were required to assess the power level of the burn. The re-entrant calorimeter indicated that there were no changes in laser beam alignment on the aperature during a run; however, the proximity of the calorimeter to the heated free jet causes drift and zero errors on the total power indication. The salt flat power shows that the laser produced the same total power incident on the aperature and is taken as the power level if the re-entrant calorimeter indicates there have been no beam alignment shifts.

TEST PROCEDURE:

The first series of burns were conducted using a rectangular slot for beam projection on the sample. The purpose of the rectangular beam cross section was to burn a sample evenly across the top. Fifteen samples were tested with this configuration (see Figure 4). The Mach number was M = .2 for the first 13 tests and was then increased to .3 for the 14th and .5 for the 15th. The laser power was increased at test 8 by approximately 60% due to ineffectual burns being produced.

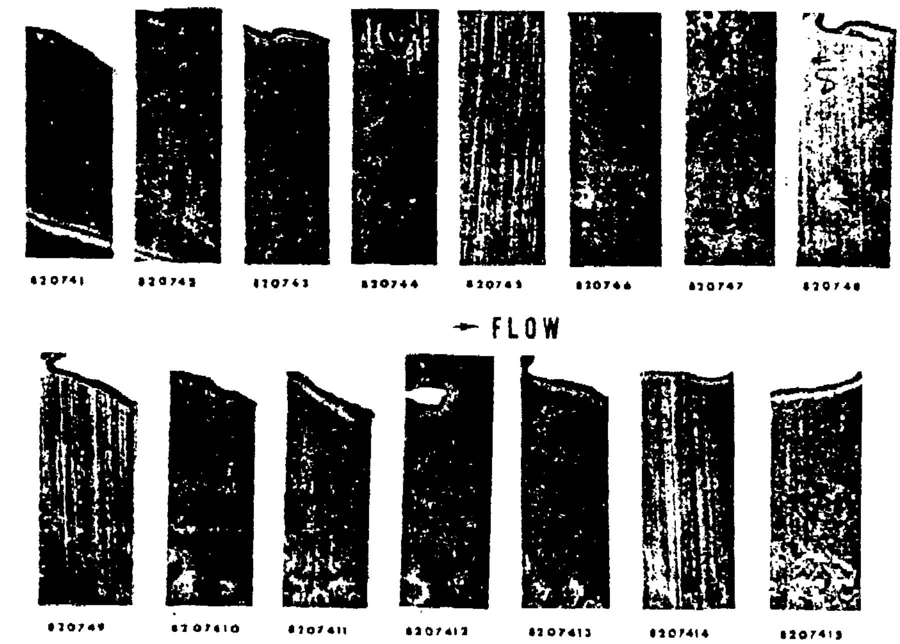


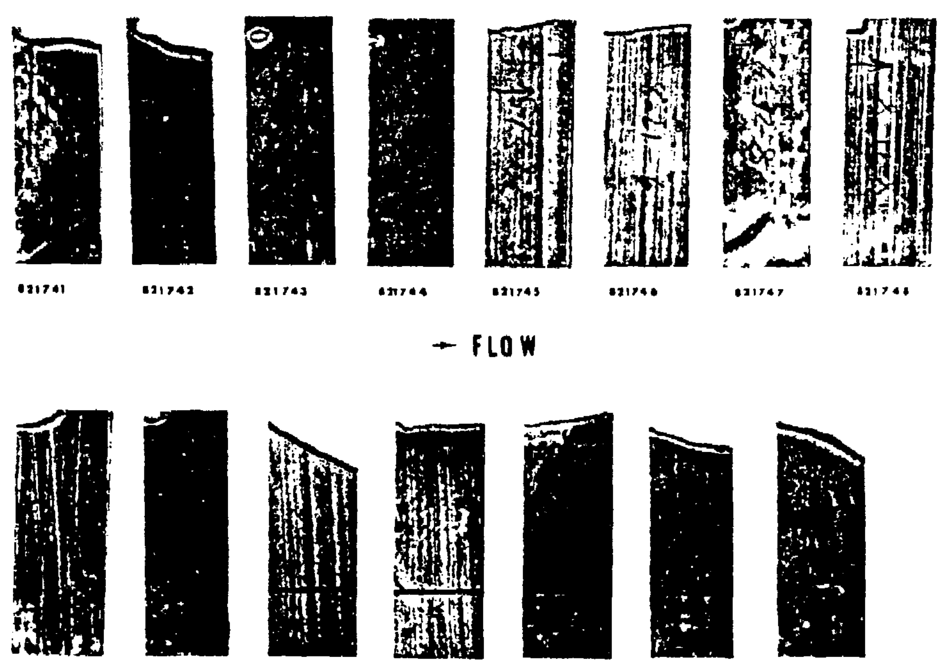
RECTANGULAR
APERATURE

QUARTER CIRCLE
APERATURE

Figure 3. Laser Aperatures

Fig 4





les

Fig 5 page 9

Figures 4 and 5. LIT Samples

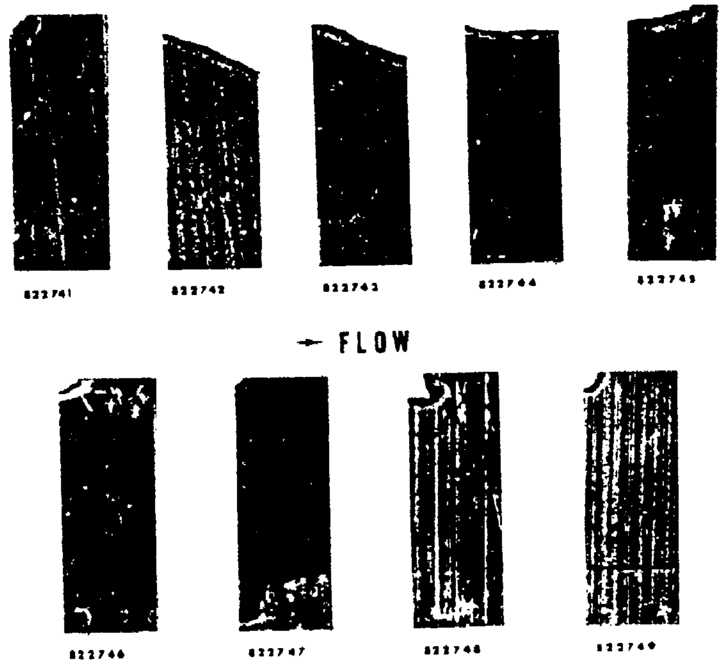
Changing the beam projection cross section from the rectangular to a quarter circle was attempted to focus the laser beam on a smaller area. Thirty-two samples were tested in this manner (see Figures 5, 6, and 7). The energy per unit area for the smaller beam would also be more consistent than with the previous rectangular section. The results verify this conclusion and consistent burns were established except for samples 821743 and 821744 where the samples lifted in the holders, and samples 821747, 821748, 821749, 8217410, and 822746, where insufficient material from the leading edge was heated. Review of the films tend to suggest poor laser alignment with the sample. Additional care was exercised in placing the remaining samples in the holder, which seemed to eliminate this problem.

The remaining samples were ignited with the smaller beam projection and variable flow and temperature conditions. The Mach number was varied from .2 to .7 and the temperature from 90°F to 400°F.

TEST RESULTS:

The results of the rectangular laser projection were inclusive related to sample exposure and burn progression. Problems arose with the burn initiation site. Inconsistent burns were developed, part of which related to the energy profile produced in the beam. The beam has a Gaussian energy distribution resulting in an uneven sample irradiation. Figure 4 illustrates the burn locus problem. Sample 820744 has

Fig 6



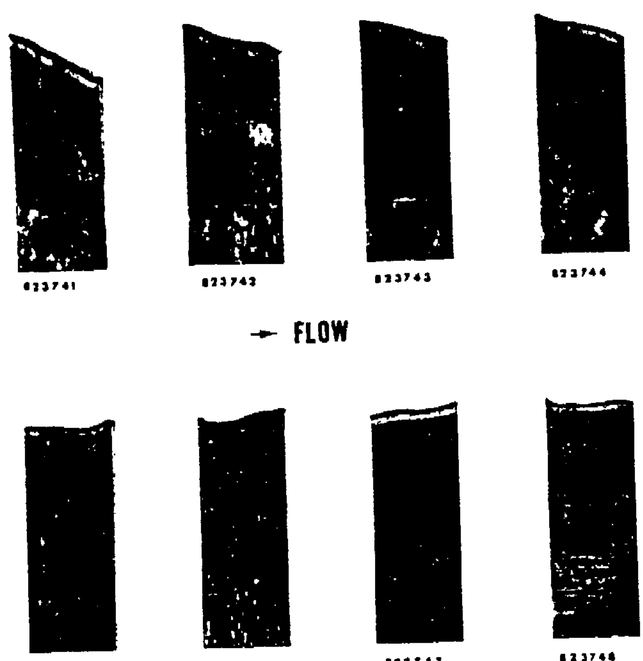


Fig 7 p. 11

Figures 6 and 7. LIT Samples

a centrally located hot spot indicating a weak energy source and an uneven distribution. Samples 820745 and 820746 were not lased by the high energy portion of the beam at all, since the samples had slipped in the holder. The laser power was increased at sample 820748 from 250 w/cm^2 to 450 w/cm^2. The power increase helped but still produced spurious results. At this point, the laser on time was doubled to ensure burn-through and sample ignition. Ignition occurred satisfactorily in each of the succeeding burns with the exception of sample 722746 which was a misalignment problem. The combination of increased beam energy and laser projection time will be used in future tests where pressure, temperature, and flow will vary.

In all conditions where good ignition, at least a one-fourth inch radius quarter circle was melted from the tip, was effected. The samples continued to burn for a finite time, up to 12 seconds. The low flow conditions, Mach .2, produced the most consumed metal. The amount of metal consumed in the burn decreased as the Mach number was increased. At low flow conditions, more metal was removed from the trailing edge than the leading edge. The reverse was true as Mach number increased. Increasing the wind temperature produced no discernible effect on the amount of material consumed for any of the velocity conditions.

Table 1 gives the pertinent test conditions, burn results, and general comments for unburned samples. Samples 822747,

822748, and 824749 did not produce a sustained combustion and were included to provide some guidance on samples canted 5° to 15° with respect to the flow velocity vector. As noted, none of these samples burned and additional testing was not pursued. This parameter will be examined in later closed tunnel studies.

TABLE 1

Titanium Sample Burn Rates

Sample Number	Mach Number	Temperature °F	Burn Rate
820749	.2	100	.279
8207410	.2	100	.099
8217411	.2	135	.197
823743	.2	368	.188
823744	.2	379	.264
821745	.5	90	.131
821746	.5	90	.099
8217412	.5	180	.213
823745	.5	412	.193
823748	.5	399	.233
8217413	.7	200	.170
823746	.7	412	.426

Figures 8 through 31 are examples of a burn taken at different stages of the combustion process. Figures 8 to 19 are a Mach .2 burn and Figures 20 to 31 are a Mach .5 burn. The sample in the high velocity flow was flopping back and forth at least one half inch in each direction. This unstable condition may have been a significantly contributing factor to the decreased material consumption in the high velocity burns. The flopping motion would tend to aid the heat removal process and effectively quench the combustion process. Future tests will need to address this problem and provide some stabilizing features in the holder design and possibly increase the sample size.

As noted in the photographs, the lumination from the combustion process is high, making the burn surface impossible to accurately determine. Estimates can be made, however, by noting before and after conditions of the sample at several stages in the combustion. One feature of particular note is the continuing process of melt, melt build-up, and sporadic melt removal during combustion. This does not follow the continuous removal assumption of M. Glickstein [Ref. 5] in his combustion model. The dynamics of the present combustion process are, however, significantly different from those analyzed in Ref. 5. The combination of high flow and high pressure could very well produce the situation of continuous or near continuous removal.

BURN RATE:

Burn rates of .4 cm/sec at 40% O_2 to 7 cm/sec at 100% O_2 was reported [Ref. 6] using 1/2 mm Ti wire. The rate was less, using 1 mm wire ranging from .2 cm/sec at 50% O_2 to 4 cm/sec at 100% O_2 concentration.

Burn rates were determined using a rectangular sample ignited with molten titanium [Ref. 4]. The rates varied from 5 - 20 cm/min. Some general trends were noted related to the environment and size changes. The rate tended to increase as the pressure was increased. The rate decreased as size was increased.

The burn rates calculated in this report were determined from:

$$R = \frac{V}{\theta A}$$

where R = burn rate - $in^3/sec\text{-}in^2$

V = volume of metal removed - in^3

θ = time of sustained combustion - sec

A = surface area supporting combustion - in^2

Movies from the tests were exhibited on a screen with a grid of 1 inch squares.

The image of the burning sample was reproduced on a data sheet with a comparable grid at successive points in the burn cycle. Each time the sample was reproduced, the frame number was noted. By measuring the area of the portion of the sample removed during combustion and multiplying that area by the thickness, the volume removed is obtained. The time of burning is determined by dividing the total frames counted by 500

frames per second, the camera speed. The burn surface was determined from the sample reproductions by measuring the length of the burn projection and multiplying that length by the material thickness. The resulting burn rates are shown in Table 1.

Due to the nature of the burn, i.e., wedge shape exposed burn area (see Figures 4 through 7), the previously presented length per second rate units were not considered applicable. Although the exact burn surface area could not be determined, the approximation method used is considered consistent for each sample and provides a more direct comparison of one burn with another. Since the more surface area exposed results in more mass consumed per unit time, the rate data should be normalized by including both the volume of metal removed and the area of the oxidizing surface.

The rate data from Ref. 6 using 1/2 mm and 1 mm wire is provided as length per unit time and is consistent with the data from this study if the exposed surface area is assumed as $\frac{\pi D^2}{4}$ where D is the wire diameter.

The rates compare quite favorably considering the difference in the circumstances of the combustion tests. The wire burn rate was .1 cm/sec at 21% O_2 and .081 cm/sec in air at 14.7 psia from this test.

CONCLUSIONS:

The use of the laser as an ignition source was found desirable. With proper precautions, the locus of ignition can be well controlled and sufficient energy, $\sim$1000 watts/cm^2, can be produced to assure ignition. The exposed area of the laser energy can be controlled by placing a copper plate with the desired beam projection shape cut in the plate center.

Temperature, pressure, and flow can also be controlled with a properly designed air tunnel. Provisions will be required for photographic coverage since that is the single most important source of data.

Care must be exercised to periodically assure the laser beam is aligned properly with the portion of the sample being exposed.

The laser quality should also be improved before additional testing is performed. A Gaussian energy distribution produces an element of error for the ignition process which is not predictable. Some non-sustained burns can result from improper ignition. A square wave energy profile is desired for this type of program.

Figures 8 through 31 are included to illustrate the illumination brilliance and the general combustion characteristics of this type of burn experiment. The melt build-up and removal process is easily observed in these photograph sequences.

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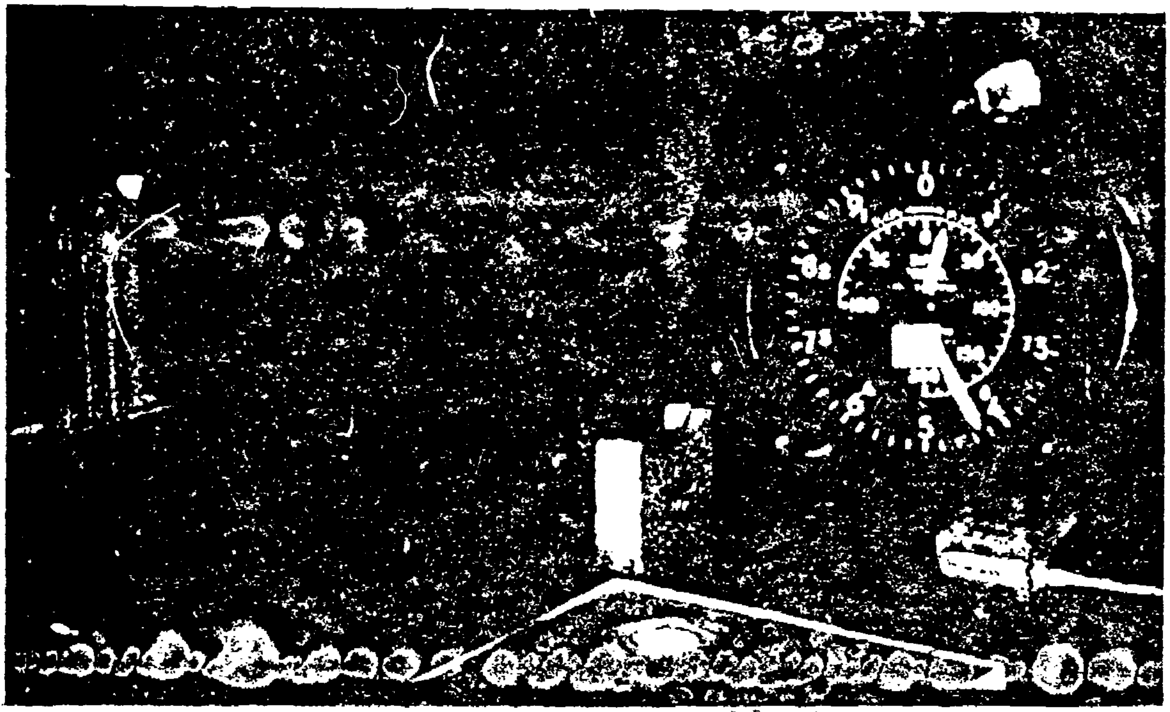
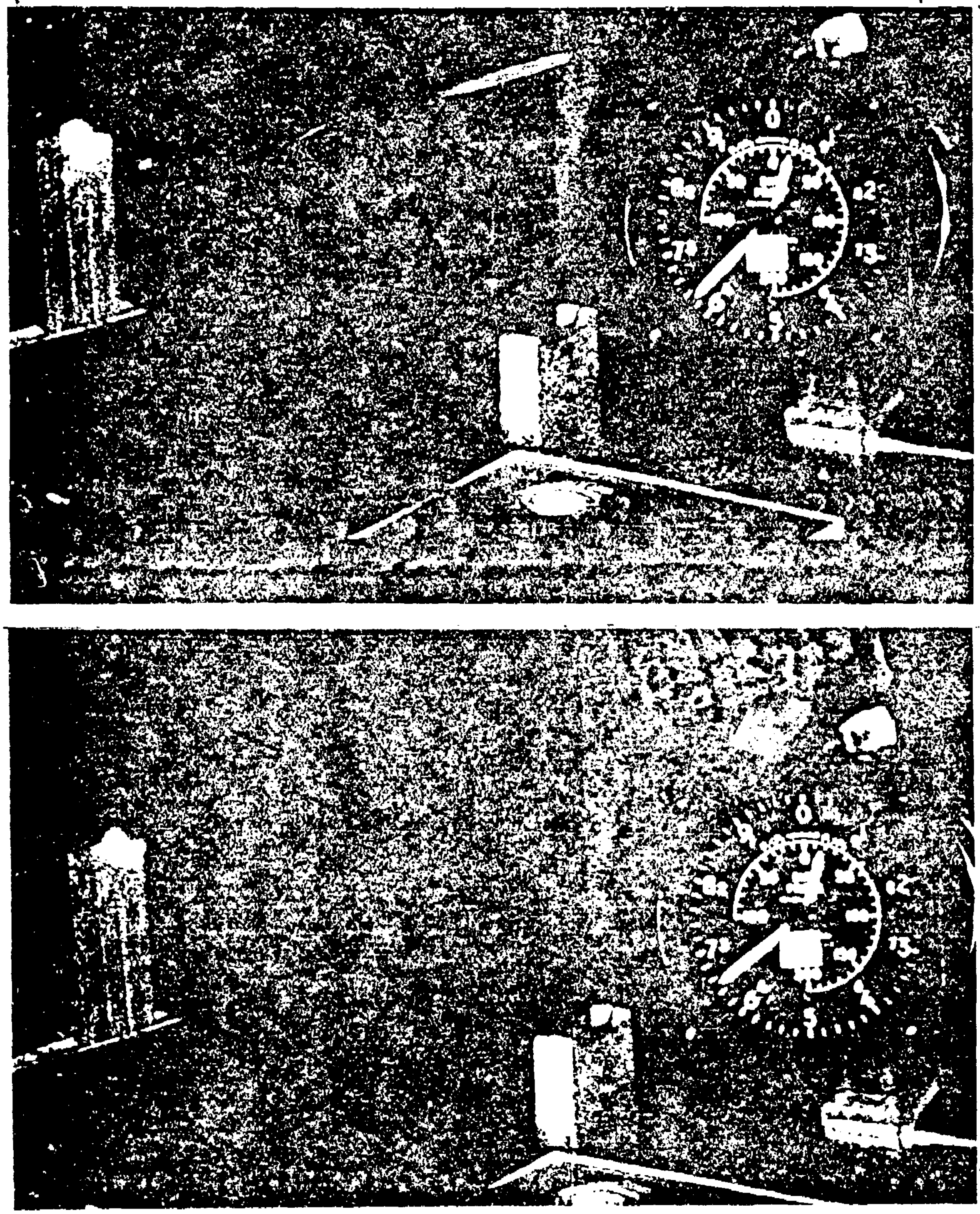
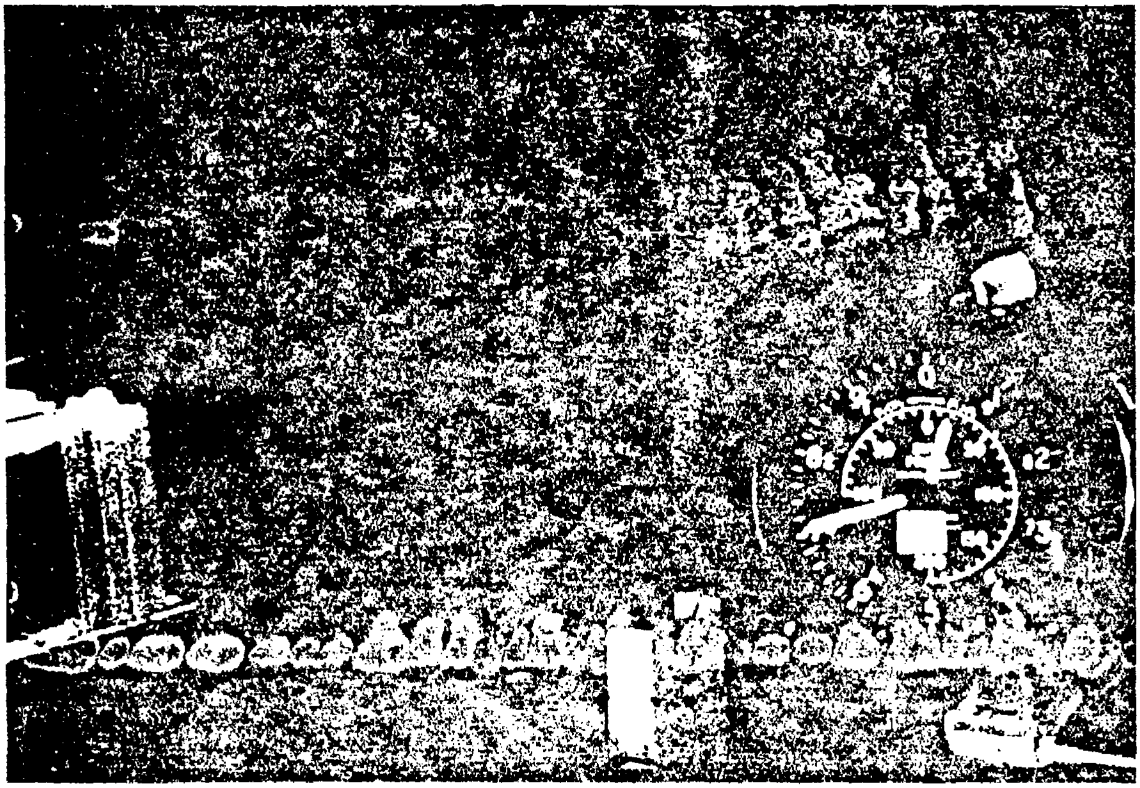
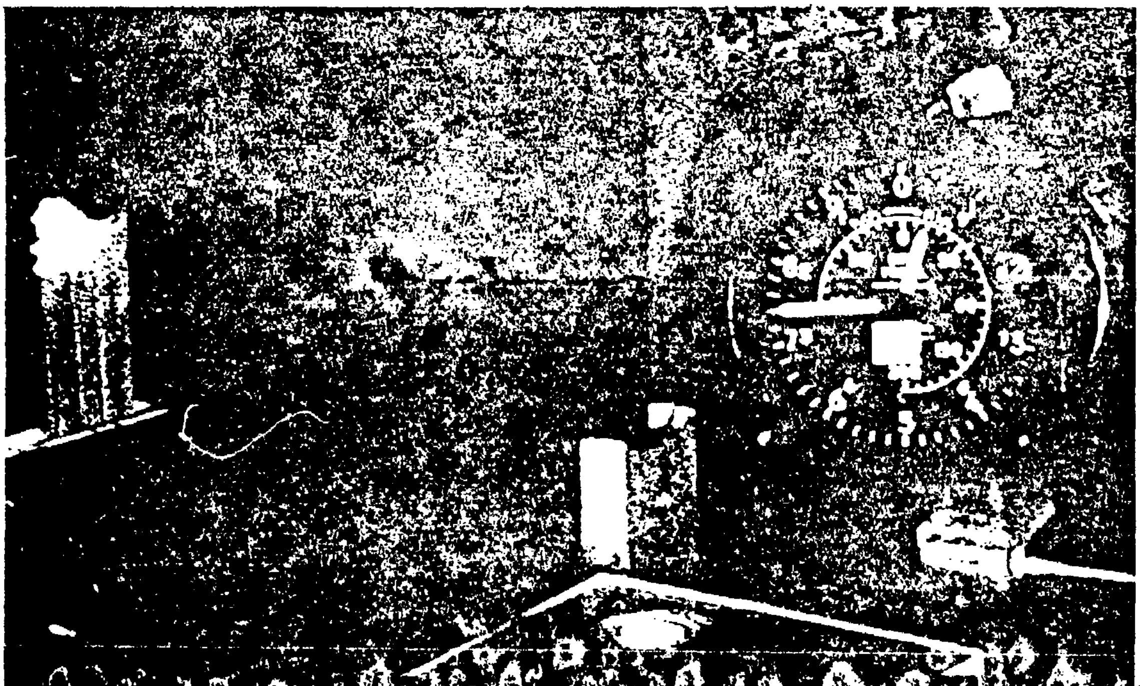


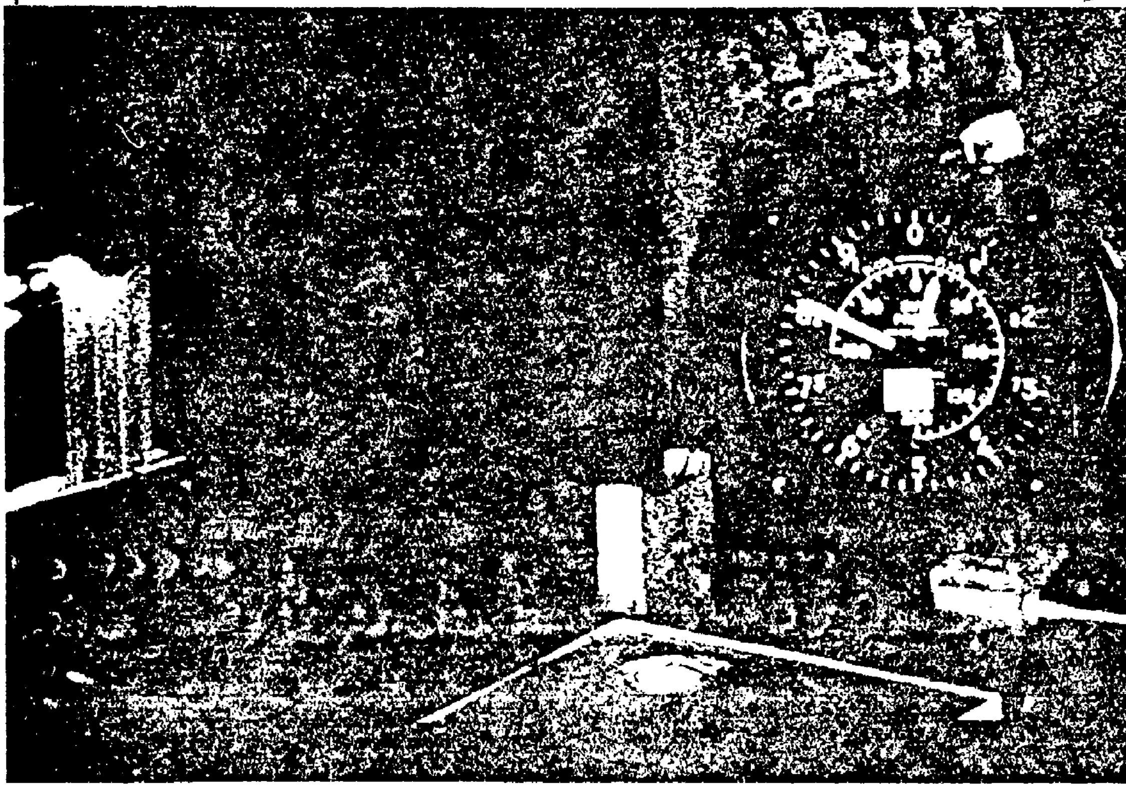
Figures 8 and 9. Mach 0.2 Ti Burn Sequence

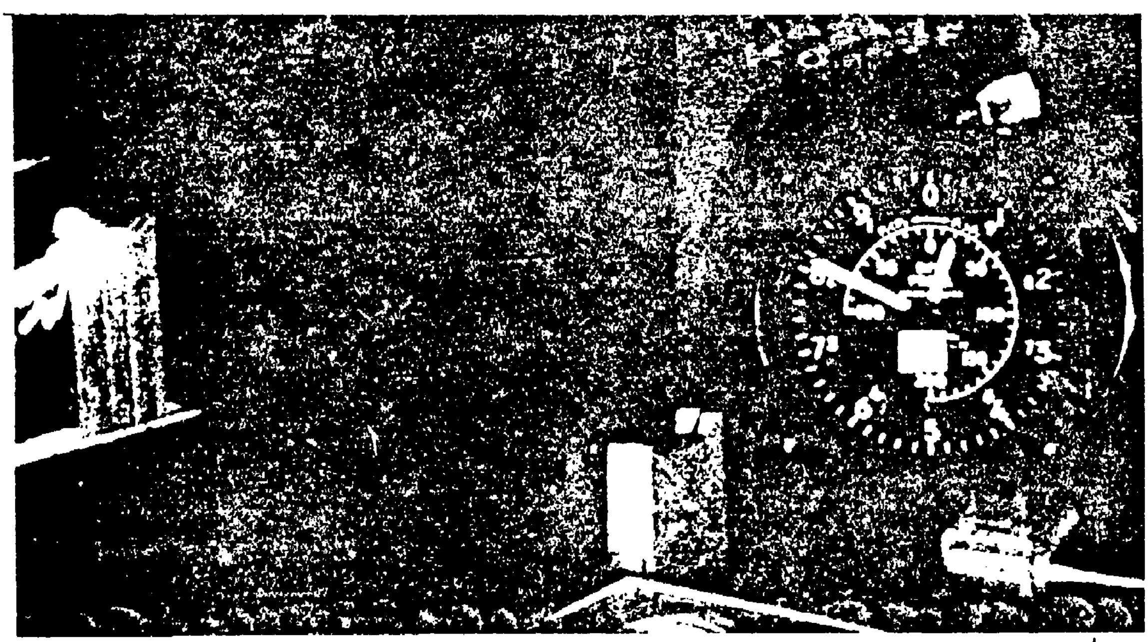


Figures 10 and 11. Mach 0.2 Ti Burn Sequence

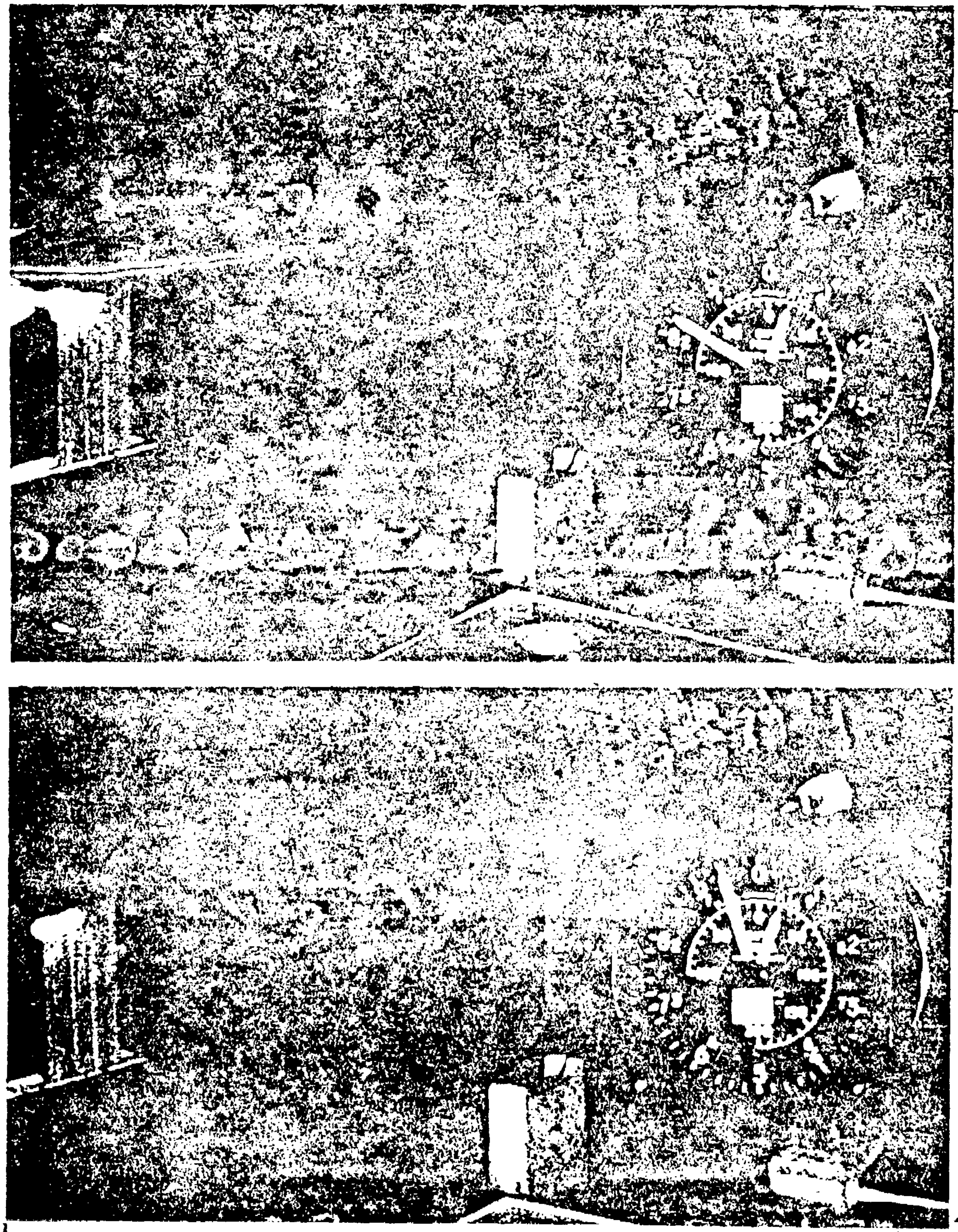




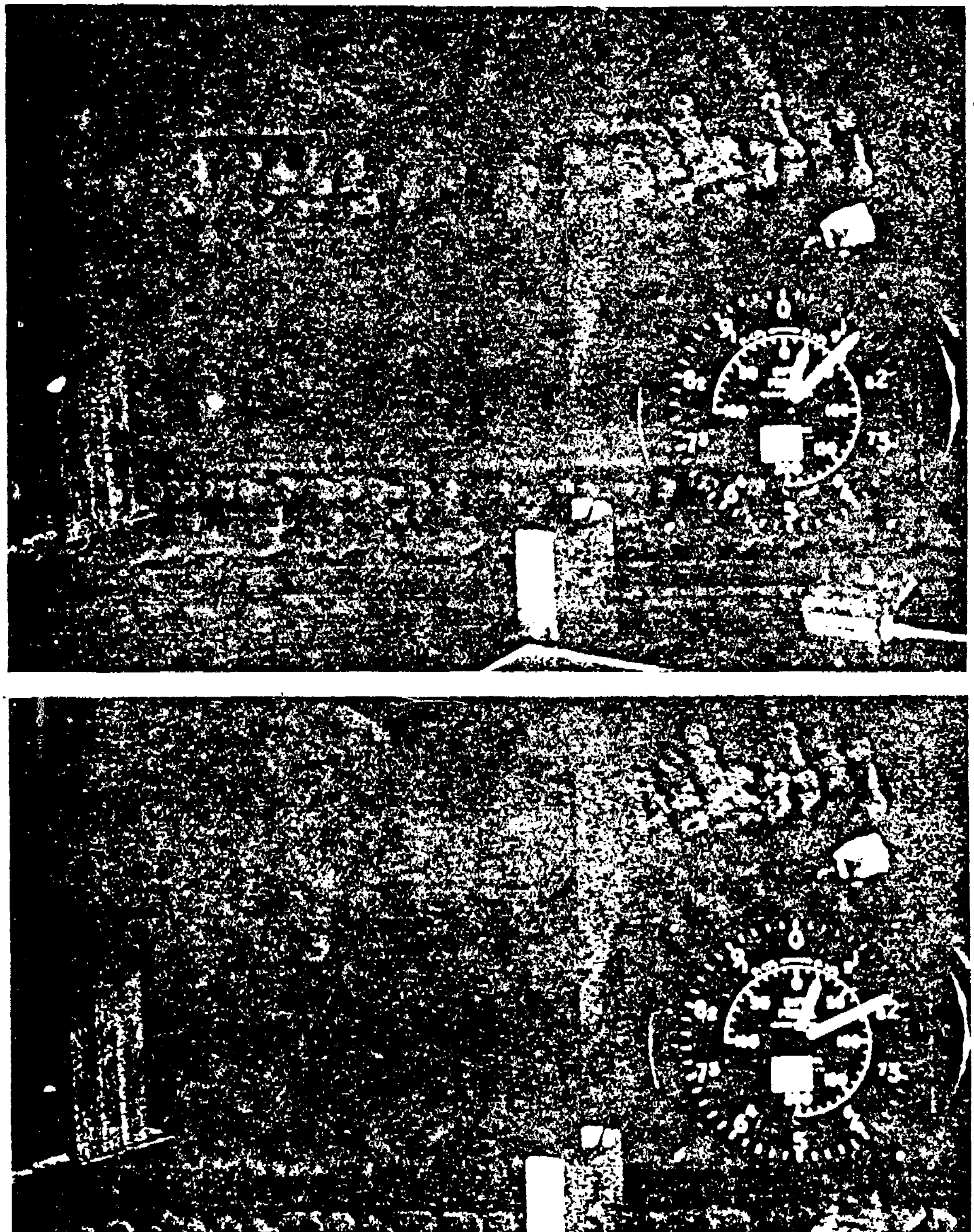




Figures 14 and 15. Mach 0.2 Ti Burn Sequence

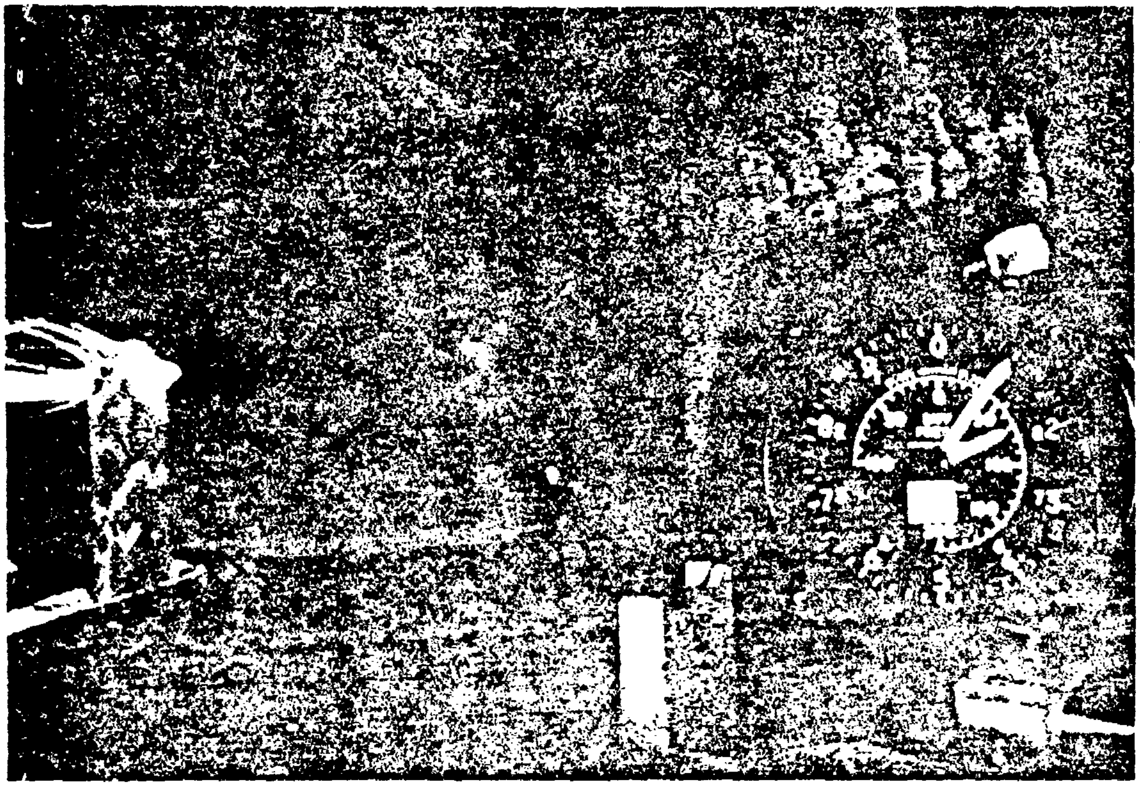


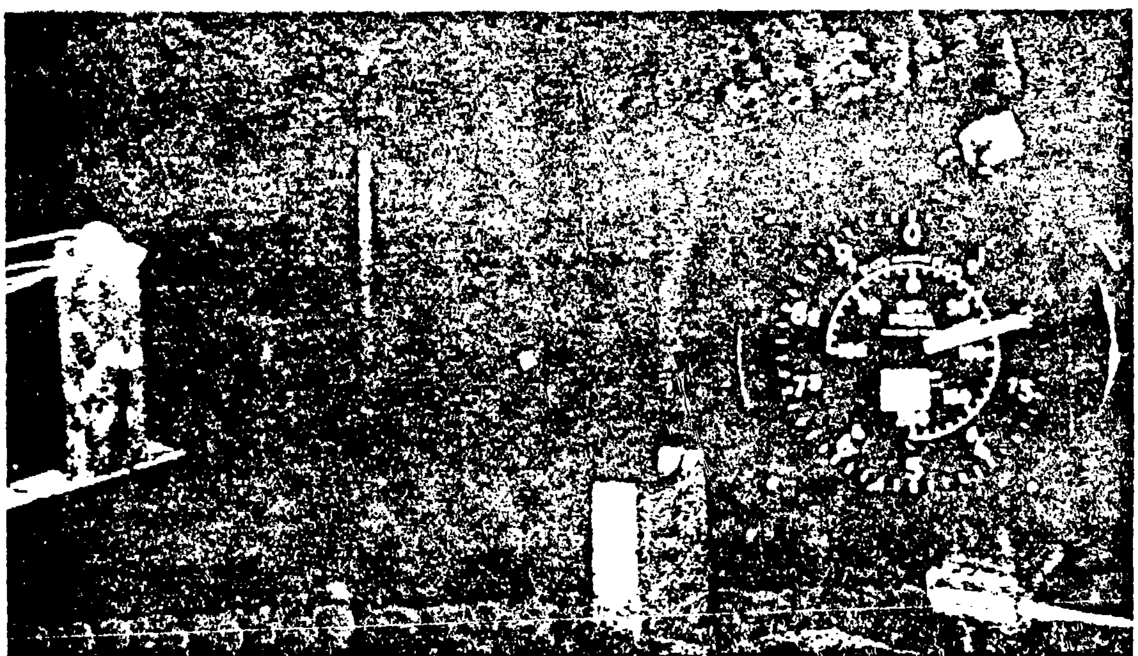
Figures 16 and 17. Mach 0.2 Ti Burn Sequence



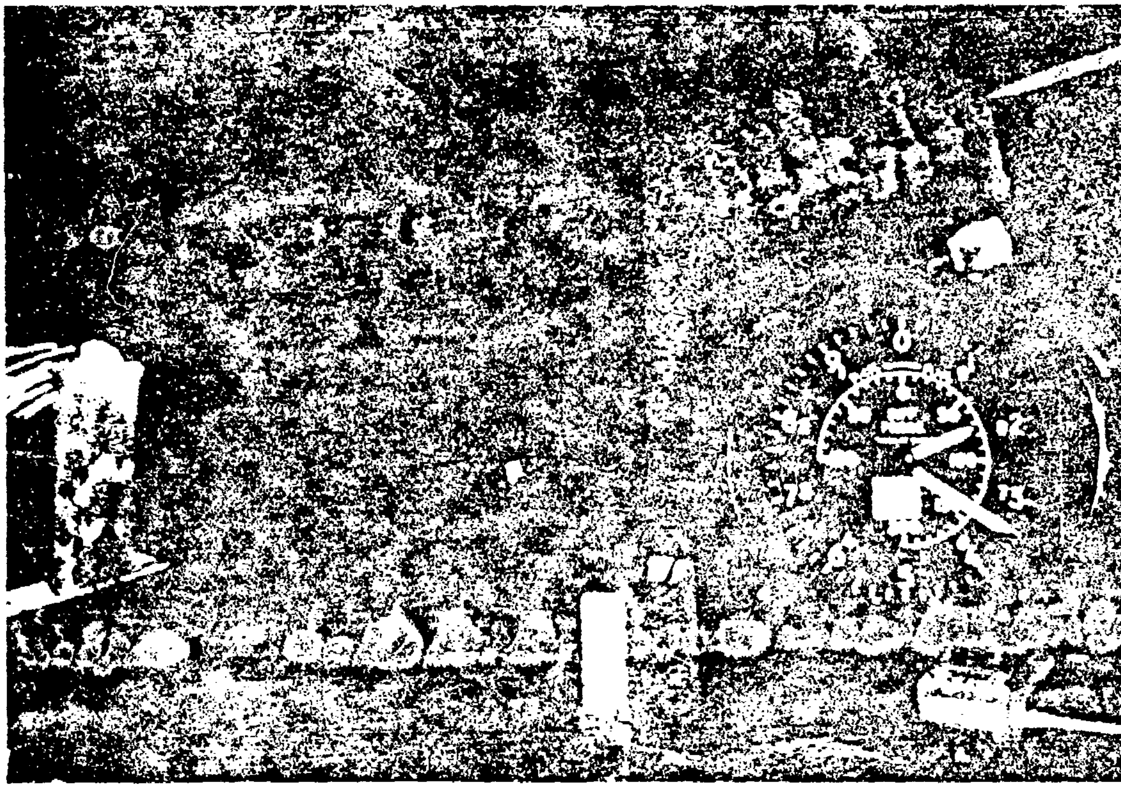
Figures 18 and 19. Mach 0.2 Ti Burn Sequence

Figures 20 and 21. Mach 0.5 Ti Burn Sequence

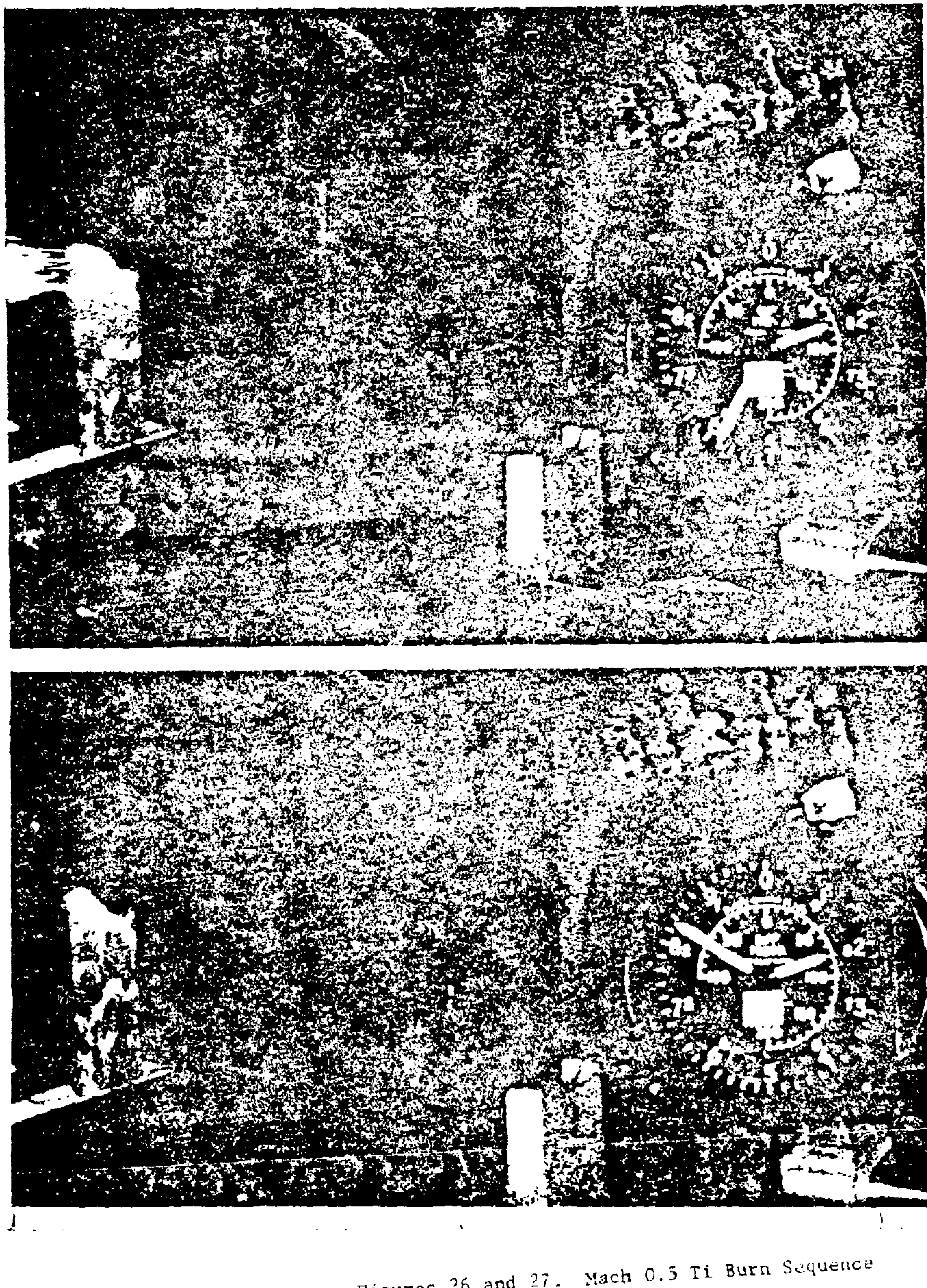




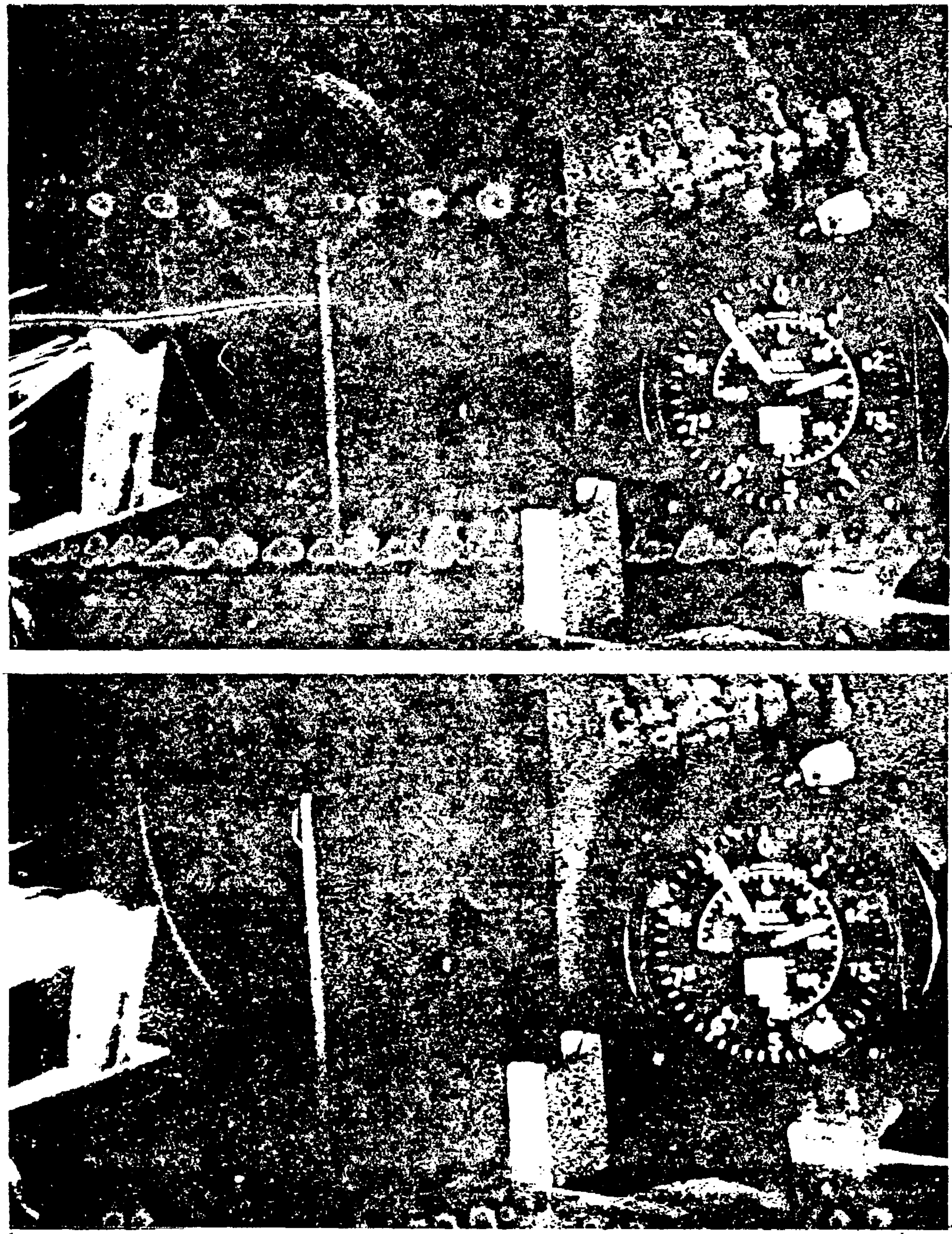
Figures 22 and 23. Mach 0.5 Ti Burn Sequence



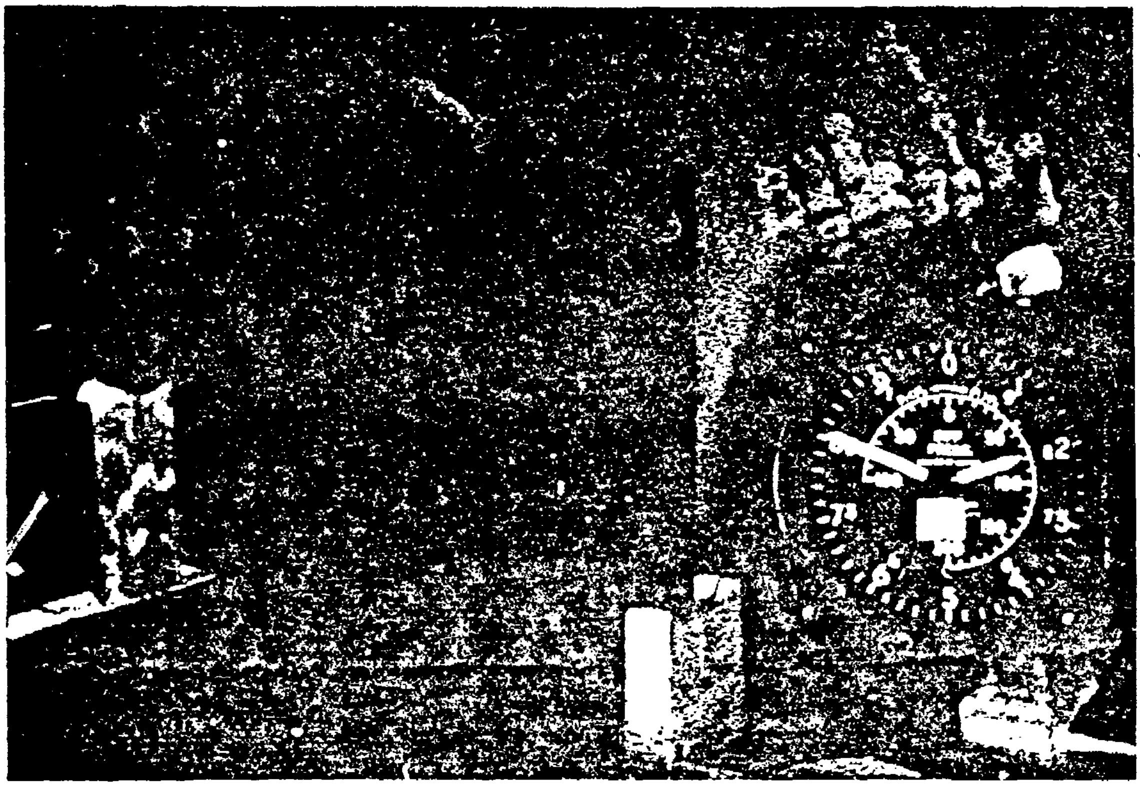
Figures 24 and 25. Mach 0.5 Ti Burn Sequence

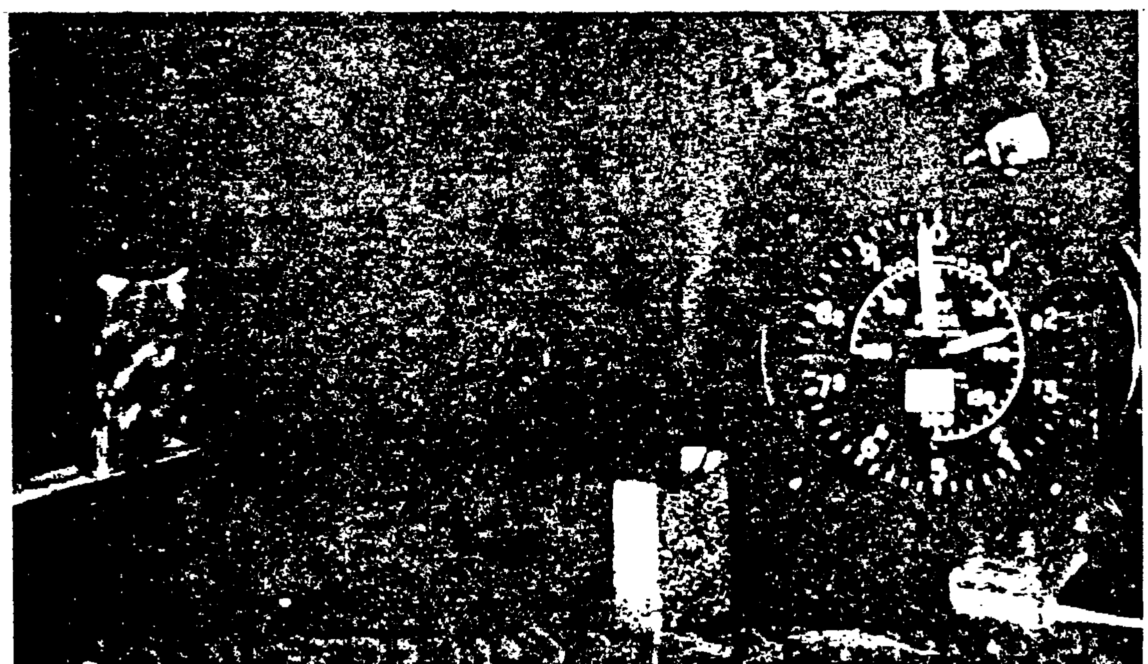


Figures 26 and 27. Mach 0.5 Ti Burn Sequence



Figures 28 and 29. Mach 0.5 Ti Burn Sequence





Figures 30 and 31. Mach 0.5 Ti Burr Sequence